Undersea Biomedical Research, Vol. 13, No. 2, June 1986

Central nervous system oxygen toxicity in closed circuit scuba divers II

F. K. BUTLER, Jr., and E. D. THALMANN

U.S. Navy Experimental Diving Unit, Panama City, FL 32407

Butler FK Jr, Thalmann ED. Central nervous system oxygen toxicity in closed circuit scuba divers II. Undersea Biomed Res 1986; 13(2):193–223.—Central nervous system oxygen toxicity is currently the limiting factor in underwater swimming/diving operations using closed-circuit oxygen equipment. A dive series was conducted at the Navy Experimental Diving Unit in Panama City, FL, to determine whether these limits can be safely extended and also to evaluate the feasibility of making excursions to increased depth after a previous transit at a shallower depth for various lengths of time. A total of 465 man-dives were conducted on 14 different experimental profiles. In all, 33 episodes of oxygen toxicity were encountered, including 2 convulsions. Symptoms were classified as probable, definite, or convulsion. Findings were as follows: (a) symptom classification is a useful tool in evaluating symptoms of oxygen toxicity; safe exposure limits should generally be adjusted only as a result of definite symptoms or convulsions; (b) the following single-depth dive limits are proposed:

20 fsw (6.1 msw) —240 min
25 fsw (7.6 msw) —240 min
30 fsw (9.1 msw) — 80 min
35 fsw (10.7 msw)— 25 min
40 fsw (12.2 msw)— 15 min
50 fsw (15.2 msw)— 10 min;

(c) a pre-exposure of up to 4 h at 20 fsw causes only a slight increase in the probability of an oxygen toxicity symptom on subsequent downward excursions; (d) a pre-exposure depth of 25 fsw will have a more adverse effect on subsequent excursions than will 20 fsw; (e) a return to 20 fsw for periods of 95–110 min seems to provide an adequate recovery period from an earlier excursion and enables a second excursion to be taken without additional hazard; (f) nausea was the most commonly noted symptom of oxygen toxicity, followed by muscle twitching and dizziness; (g) dives on which oxygen toxicity episodes were noted had a more rapid rate of core temperature cooling than dives without toxicity episodes; (h) several divers who had passed the U.S. Navy Oxygen Tolerance Test were observed to be reproducibly more susceptible to oxygen toxicity than the other experimental divers.

oxygen toxicity
Oxygen Tolerance Test
oxygen convulsion
exercise
hypothermia
closed circuit UBA
oxygen exposure limits

Central nervous system oxygen toxicity is currently the limiting factor in underwater swimming/diving operations using oxygen closed-circuit scuba. The present U.S. Navy oxygen diving depth/time limits for these type operations are found in the U.S. Navy Diving Manual (1) and are based on work done at the Navy Experimental Diving Unit (NEDU) by Lanphier and Dwyer (2). Other work done at NEDU in 1980 (3) and earlier work by Donald (4) indicated that a threshold for CNS oxygen toxicity may exist at 20–25 fsw and that very long exposures in this depth range may be possible. Additionally, there was interest in exploring the feasibility of making downward excursions after a pre-exposure at a depth of 20–25 fsw. This prompted a 1982 study at NEDU (5) which showed: (a) oxygen convulsions are possible at 25 fsw after a 72-min exposure (an exposure previously thought to be free of oxygen toxicity convulsions); (b) the current closed-circuit scuba oxygen exposure time at 40 fsw could probably be extended to 15 min but not to 20 min; (c) a 1-h pre-exposure to closed-circuit oxygen at 25 fsw does not significantly decrease the safe exposure time at 40 fsw but a 2-h pre-exposure seems to.

Building on the findings of the studies cited above, the present study was designed to find the deepest depth at which a 4-h closed-circuit scuba oxygen exposure could be safely performed and to investigate more fully the effects of pre-exposures at shallower depths on subsequent downward excursions. Because of the decreased safe exposure time for downward excursions noted after 2 h at 25 fsw (5), the pre-exposure depth was changed to 20 fsw for this study.

METHODS

Divers

All subjects were U.S. Navy divers either stationed at U.S. Navy Experimental Diving Unit or on temporary duty from Fleet units. A total of 53 individuals participated and their physical characteristics are given in Table 1. The Draeger LAR V closed-circuit oxygen Underwater Breathing Apparatus (UBA) (Draegerwerk, Lubeck, Germany) was used for all studies (6). All divers were made thoroughly familiar with the operation of the LAR V and were thoroughly briefed on the recognition of the signs and symptoms of CNS oxygen toxicity; training dives were conducted before beginning the experimental dives, and emergency procedures were thoroughly rehearsed.

Apparatus, measurements, and conditions

All dives in this study were conducted in the Navy Experimental Diving Unit's Ocean Simulation Facility (OSF) complex in Panama City, FL. The overall dimensions of the cylindrical wet chamber are 47 ft (length) by 15 ft (internal diameter); for this dive series, a special platform 14 by 25 ft was constructed and placed in the wet chamber such that the platform was 4.5 ft below the water surface. Four electrically braked pedal mode ergometers (7) on specially built frames were mounted on the platform which allowed the diver to pedal in the prone position approximately 1 fsw below the surface of the water. The shallow depth of the diver in the water column minimized the possibility of a gas embolism in the event of an underwater convulsion

TABLE 1
DIVER PHYSICAL CHARACTERISTICS

Diver No.	Height, cm	Weight, kg	Age	Diver No.	Height, cm	Weight, kg	Age
1	177.8	77.3	24	28	175.3	85.9	37
2	182.9	79.1	24	29	188.0	86.4	22
3	177.8	79.6	24	30	180.3	91.8	29
4	185.4	83.6	25	31	172.7	73.6	25
5	177.8	84.1	22	32	175.3	79.6	35
6	175.3	77.3	24	33	175.3	80.0	27
7	188.0	100.0	25	34	193.0	83.6	33
8	182.9	84.1	29	35	175.3	71.4	43
9	177.8	79.6	22	36	180.3	75.0	36
10	172.7	70.5	20	37	170.2	72.7	32
11	180.3	83.6	21	38	180.3	79.6	24
12	172.7	63.6	25	39	172.7	68.2	27
13	177.8	80.9	22	40	177.8	70.5	25
14	182.9	86.4	23	41	182.9	93.2	31
15	182.9	79.6	22	42	188.0	90.0	29
16	193.0	81.8	27	43	175.3	70.5	35
17	152.4	86.4	24	44	180.3	94.1	31
18	177.8	71.4	23	45	182.9	80.0	39
19	175.3	53.2	28	46	177.8	84.1	39
20	177.8	69.6	22	47	185.4	96.4	30
21	182.9	83.6	43	48	185.4	94.6	41
22	188.0	87.7	29	49	167.6	69.6	32
23	190.5	101.4	37	50	182.9	86.4	41
24	175.3	72.7	45	51	172.7	70.6	36
25	172.7	79.1	27	52	172.7	78.6	39
26	180.3	84.6	37	53	185.4	84.1	35
27	188.0	118.2	37				
	Mean 179.3 ± 6.98	81.5 ± 10.4	29.9 ± 6.9				

and allowed the diver to get his head out of the water merely by standing up. Profile depth was established by pressurizing the OSF to 1 ft shallower than the required depth, the water column of 1 ft establishing the correct depth relative to the midline of a prone diver. All dive subjects wore safety harnesses which could be snapped into an overhead safety hoist to facilitate safe evacuation from the wet chamber in the event of a convulsion or a severe oxygen toxicity episode.

The Draeger LAR V is a relatively simple closed-circuit oxygen UBA consisting of a breathing bag connected to an inhalation hose with a CO_2 absorbent canister between the exhalation hose and the breathing bag (Fig. 1). Oxygen is added to the breathing bag automatically by a demand valve actuated during inhalation when the bag collapses or manually through a bypass valve.

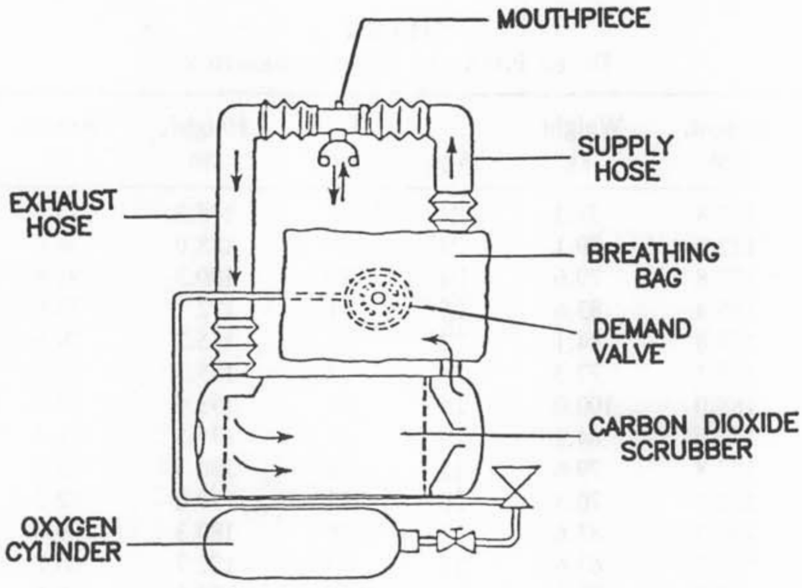

Fig. 1. Gas flow diagram of the Draeger Lar V closed-circuit oxygen underwater breathing apparatus.

Draeger LAR V UBAs with standard mouthpieces had a 1-ft gas sample line (⅛″ i.d.) installed in the carbon dioxide canister effluent coupling terminating in a quick-disconnect fitting. Upon entering the chamber, divers connected the UBA sample line to a chamber sample line (⅛″ o.d.) which routed the canister effluent samples to either a Perkin Elmer MGA 1100 (Perkin Elmer Aerospace Division, Pomona, CA) or Chemetron Medspect 2 (Chemetron Medical Products, St. Louis, MO) mass spectrometer. Gas samples were taken continuously at a flow rate of 100 cm^3/min; oxygen and carbon dioxide levels were recorded every 30 s by an HP-1000 Computer (Hewlett Packard, Cupertino, CA) and monitored on a display.

A Validyne DP-15, 3000 psi ($2.07.10^4$ kPa ± 0.5%) pressure transducer (Validyne Engineering, Northridge, CA) specially modified for submerged use was mounted on the high pressure side of the LAR V regulator to give a continuous reading of oxygen bottle pressure, which was monitored and recorded every 30 s by the HP-1000 Computer. This transducer was calibrated with a quartz borden tube digital depth gauge (accuracy ± 1 psi) before and after each experiment. Oxygen consumptions were calculated by measuring the pressure drop vs. time for selected portions of the dive. Since the oxygen bottle volume was known, these pressure drop rates could be corrected for temperature and gas sample rates to give an estimate of diver oxygen consumption in liters per minute (STPD). Occasional purging of the UBA was evident on oxygen bottle pressure read-outs and these pressure changes were not considered in estimating oxygen consumption. Oxygen consumptions were calculated separately for the work-rest periods and the continuous exercise periods (discussed below).

Water temperature was maintained at 21.7°C (71°F) for the majority of the dive series and the divers were allowed to wear wetsuit tops or "shorty" wet suits (⅛″ or 3/16″ thickness). During the cold water profiles 12.8°C (55°F), the divers were permitted to dress in full ¼″ wet suits. These temperature-thermal protection combinations were designed to produce a core temperature drop rate of approximately 0.25°C/h.

On the 4-h (and longer) profiles, diver core temperature was continuously monitored using a YSI 702-A rectal probe (Yellow Springs Instrumentation, Yellow Springs, OH). The dive was terminated if the diver's core temperature dropped below 35°C (95°F) provided it had dropped at least 2°C from predive baseline.

Experimental profiles and procedures

The experimental profiles are listed in Table 2 and were divided into short and intermediate single depth profiles, and long single and multiple depth (excursion) profiles. These profiles were established by combining operational considerations with the findings of previous experimental oxygen dive series (2–5, 8). Profiles were either exposures at a single depth (square dives), a 4-h pre-exposure at 20 fsw followed by a downward excursion at the End (E profiles), a 2-h pre-exposure at 20 fsw followed by a downward excursion in the Middle, and then another 2 h (less the excursion time) exposure at 20 fsw (M profiles) or a 2 h pre-exposure followed by a downward excursion in the Middle followed by another exposure at 20 fsw and another downward excursion at the End of 4 h (EM profiles). Ascents and descents for the excursions were accomplished by traveling for 1–2 min before and after the noted excursion times; thus the entire time noted for the excursion was spent at the designated excursion depth.

Four dive subjects were present on each dive. Divers dressed and donned their UBAs outside of the chamber, entered the wet chamber, connected the monitoring umbilical, and were compressed to depth breathing air standing on the platform with their heads out of the water. At depth, divers performed a "purge" procedure (consisting of filling the breathing bag with oxygen and exhaling to atmosphere) until the oxygen fraction exceeded 95% as monitored on the mass spectrometer. The figure of 95% was chosen as a reasonable "worst case" figure for oxygen fraction (9). During the study, additional purges were done if the oxygen fraction fell below 95%. Only after all divers had completed their purge and were ready to begin exercising on the ergometers was profile time begun. Thus, the period of oxygen breathing at depth was generally 1–2 min in excess of the time shown on the profiles.

The divers pedaled on the ergometers continuously at 50 W for the entire duration of the short profiles and the downward excursions on the long profiles. On the intermediate 30 fsw profile and the 20 fsw periods on the long profiles, the divers exercised on 6 min work-4 min rest cycles. This exercise rate was designed to approximate that of an underwater swimmer swimming at a comfortable rate (0.8 knots) which results in an oxygen consumption of approximately 1.3 liters/min (10). Each diver was monitored at all times by his own tender, who was positioned immediately adjacent to the diver. In addition, a standby diver equipped with air scuba gear was present in the wet chamber; a diving corpsman and safety hoist operator were present at depth in the dry trunk immediately above the wet chamber; and a qualified NEDU Diving Medical Officer was present outside the chamber at all times during the dives.

All personnel in the wet chamber had been thoroughly briefed on the recognition of the signs and symptoms of CNS oxygen toxicity. Divers continued on the prescribed exercise protocol until symptoms consistent with CNS oxygen toxicity were observed either by the diver himself or his tender or until the profile was finished.

TABLE 2
EXPERIMENTAL DIVE PROFILES

Profile	Depths, fsw (msw)	Times, min
	SHORT	
35–30	35 (10.7)	30
35–25	35 (10.7)	25
40–15	40 (12.2)	15
50–5	50 (15.2)	5
50–10	50 (15.2)	10
	INTERMEDIATE	
30–90	30 (9.1)	90
	LONG	
25–240	25 (7.6)	240
35 M–25	20 (6.1)	120
	35 (10.7)	25
	20 (6.1)	95
35 E–25	20 (6.1)	240
	35 (10.7)	25
35 EM–25	20 (6.1)	120
	35 (10.7)	25
	20 (6.1)	95
	35 (10.7)	25
40 M–15	20 (6.1)	120
	40 (12.2)	15
	20 (6.1)	105
40 E–15	20 (6.1)	240
	40 (12.2)	15
50 M–10	20 (6.1)	120
	50 (15.2)	10
	20 (6.1)	110
50 EM–10	20 (6.1)	120
	50 (15.2)	10
	20 (6.1)	110
	50 (15.2)	10

First two digits of profile description are deepest depth (fsw). E = Excursion at *END* of profile; M = excursion at *MIDDLE* of profile; EM = Excursion at *END* and *MIDDLE* of profile. Number following hyphen is time spent at deepest depth.

Since the long profiles exceeded the normal duration of the Draeger LAR V UBA, a spare UBA for each diver was prepared. If canister effluent CO_2 (as monitored by the mass spectrometer) exceeded 1% surface equivalent value (SEV) (7.6 mmHg) for

2 continuous min or 1.5% SEV (11.4 mmHg) at any time or if oxygen bottle pressure dropped below 500 psi, the diver was directed to change his UBA during a rest period. UBA changes were designed to avoid any significant drop in oxygen partial pressure. The diver continued breathing from a UBA throughout, holding his breath as he switched from the expended UBA to the second UBA. The constant monitoring of CO_2 eliminated the possibility of a significant increase in inspired CO_2, which has been shown to potentiate CNS oxygen toxicity (11–13).

RESULTS

A total of 459 man-dives were either completed or resulted in toxicity episodes. Of these, 50 were done in 12.8°C (55°F) while the remainder were done in 21.7°C (71°F) water. Six additional man-dives were attempted but were terminated just before completion as a result of another diver experiencing a convulsion. Table 3 provides a summary of the dives accomplished and the toxicity episodes that occurred on each profile. The toxicity episodes were assigned to one of three categories: (a) convulsion; (b) definite; or (c) probable.

TABLE 3
SUMMARY OF DIVES BY PROFILE

Profile	Man Dives, No.	Subjects, No.	Water Temperature	Toxicity Episodes: Convulsion	Definite	Probable
25–240	22	15	21.7°	0	0	0
30–90	37*	25	21.7°	1	0	0
35–30	40	27	21.7°	0	4	1
35–25	47	23	21.7°	0	0	0
35 M–25	20	17	21.7°	0	1	1
35 E–25	19	15	21.7°	0	1	4
35 EM–25	16	15	21.7°	0	0	3
40–15	40	23	21.7°	0	0	1
40 M–15	19	16	21.7°	0	0	0
40 E–15	16**	13	21.7°	1	0	0
40 E–15	25	12	12.8°	0	0	3
50–5	57	22	21.7°	0	0	0
50–10	58	33	21.7°	0	0	1
50 M–10	18	16	21.7°	0	1	1
50 EM–10	25	10	12.8°	0	2	7
Total	459†			2	9	22

*Three additional man-dives were completed to a time of 82 min at which time they were aborted because the 4th diver suffered a convulsion. **Three additional man-dives were completed to a time of 242 min at which time they were aborted because the 4th diver suffered a convulsion. †A total of 465 man-dives were attempted but only 459 were completed or resulted in toxicity episodes.

Toxicity episode classification

Note that "oxygen toxicity episode" refers to any combination of signs and symptoms occurring in a diver. Some episodes consisted of only one sign or symptom while other episodes consisted of several signs or symptoms. The convulsion category requires no further elaboration except to say that both convulsive episodes were of the classic grand mal, tonic-clonic type. Definite refers to episodes that were felt to have a high probability of resulting from oxygen toxicity. Episodes in which signs or symptoms such as muscle twitching, confusion, aphasia, and visual disturbances occurred would generally result in a definite classification. It should be emphasized, however, that other factors were also considered in determining the classification of a particular toxicity episode. Among these factors were the condition of the diver as noted by observers, whether or not the dive was stopped when the symptoms occurred, and the duration and severity of the symptoms. Probable episodes were those that were probably a result of CNS oxygen toxicity but which were more equivocal than those placed in the definite category. Episodes consisting solely of symptoms such as nausea, dizziness, numbness, tingling, lightheadedness, or poor concentration generally resulted in the toxicity episode being classified as probable.

Results by profile

Figures 2–5 are a graphic representation of each profile showing the time of occurrence and type for each oxygen toxicity episode. The three digit number following the P, D, or C symptom code is the dive number and keys that particular symptom to the more detailed description in Table 4.

The order in which the profiles are presented in Fig. 2–5 and Tables 3 and 4 do not represent the order in which profiles were tested. Safe exposure times for square dives to 35, 40, and 50 fsw were first determined. The initial 30-min exposure time at 35 fsw (Profile 35–30) resulted in 5 symptoms, 4 of which occurred at 25 min or later. Shortening the exposure time to 25 min (Profile 35–25) eliminated symptoms. The 40 fsw for 15 min profile (40–15) was presumed safe from a previous study (5) and 40 man-dives with only 1 probable symptom confirmed this presumption. The complete absence of symptoms after a 5-min exposure at 50 fsw (50–5) led to doubling of the exposure time which resulted in only 1 probable symptom in 58 man-dives.

Twenty-two square dives to 25 fsw for 240 min resulted in no symptoms. At 30 fsw for 90 min, only one symptom occurred in 37 man-dives, but this was a convulsion.

All other profiles tested were excursion profiles. The so-called pre-exposure depth was chosen as 20 fsw instead of 25 fsw as it was in the 1982 NEDU study (5) because there appeared to be a decrease in safe exposure time on downward excursions after a 2-h pre-exposure at 25 fsw. The square dive exposure time limits which had been previously determined for a given depth, as discussed above, were used for all downward excursions whether they occurred in the middle or at the end of the profile. Initially, it was planned to do E, M, and EM type profiles with excursions to 35, 40, and 50 fsw but time limitations prevented all combinations from being tested. Also, it was initially planned to only test profiles in 12.8°C (55°F) water which had been tested at 21.7°C (71°F), but again time limitations intervened.

Profile 35 M–25 and 35 E–25 produced some probable symptoms at 20 fsw and one definite symptom during the downward excursion on each profile. The double down-

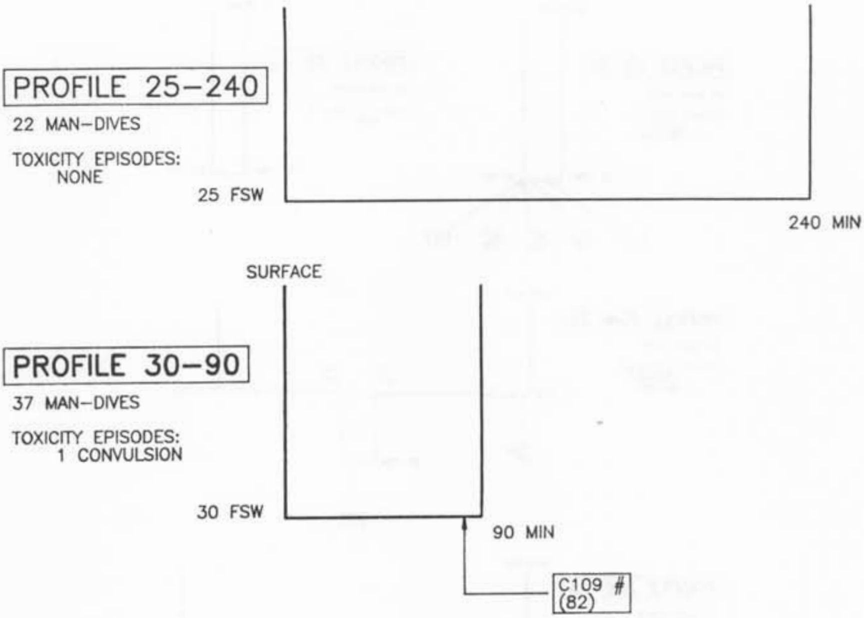

Fig. 2. Profiles 25 and 30 fsw. Symptom code: C = convulsion; D = definite; P = probable; 109 = dive no. 109 (keys to Table 5); # = all four subjects stopped; 82 = 82 min into the dive.

ward excursion profile (Profile 35 EM–25) had no definite symptoms and fewer probable symptoms than the 35 E–25 profile.

Time was available to test only two, 40-fsw downward excursion profiles. The single downward excursion in the middle of the profile (Profile 40 M–15) produced no symptoms. When the excursion was moved to the end of the profile only one symptom occurred, which was a convulsion after 2 min at 40 fsw. It should be noted that this was the same diver who convulsed on Profile 30–90. When performed in 12.8°C (55°F) water, Profile 40 E–15 produced 3 probable symptoms, all occurring at 138 min or earlier with none during the downward excursion.

A 50-fsw downward excursion after the 2 h pre-exposure at 20 fsw (Profile 50 M–10) produced one probable symptom during the ascent from 50 back to 20 fsw and another definite symptom 3 min after completing the downward excursion. Profile 50 EM–10 was performed only in 12.8°C (55°F) water and resulted in more symptoms occurring than on any other profile. A total of 9 symptoms occurred, but of these only 2 were definite and no convulsions occurred.

Oxygen consumption

Oxygen consumption data were calculated by measuring oxygen bottle pressure drop (*see* Methods). For excursions and short profiles, during which the divers were

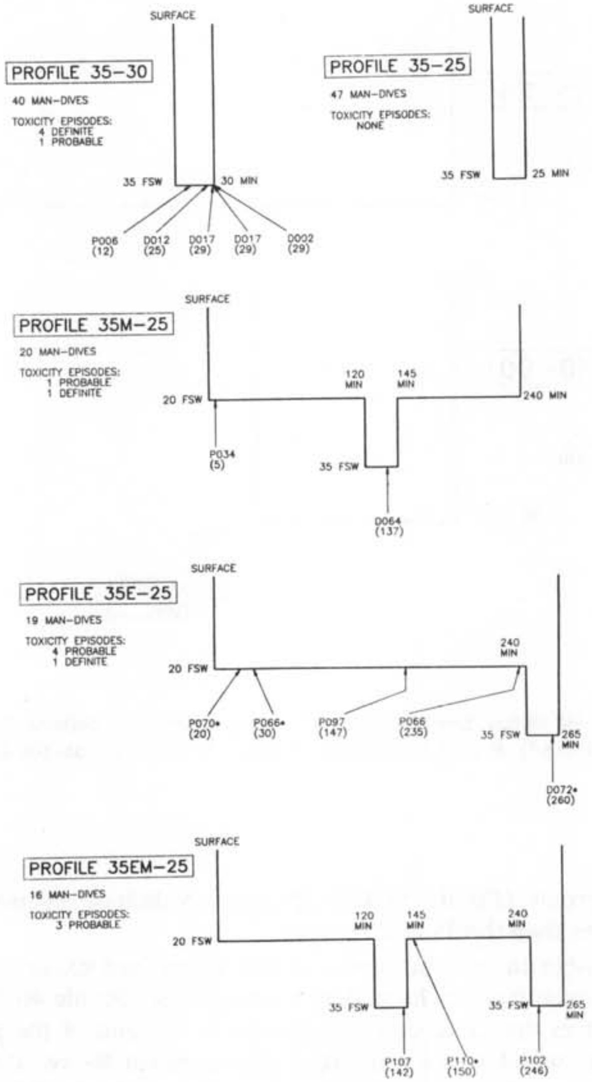

Fig. 3. Profile 35 fsw. Symptom code same as for Fig. 2. *Subject completed entire profile.

exercising continuously, the pressure drop over the entire duration of the excursion was usually used in calculating oxygen consumptions. For alternating work-rest periods, a variable time window during the first part of the dive was used. The times chosen varied in length from 1 to 3 h and depended on how long it took the diver to complete all required purging and how long the work-rest cycles continued before being interrupted by either a UBA change or an excursion. An equal number of work and rest cyles was used. Continuous exercise in 21.7°C water at 50 W produced a mean oxygen consumption of 1.66 ± 0.35 l/min (n = 78) on the short profiles and 1.67 ± 0.31 l/min (n = 37) during downward excursions on the long profiles.

With alternating work-rest cycles of 6 and 4 min, the oxygen consumption at 21.7°C (71°F) was 1.29 ± 0.30 l/min in 134 subjects. Oxygen consumptions were not mea-

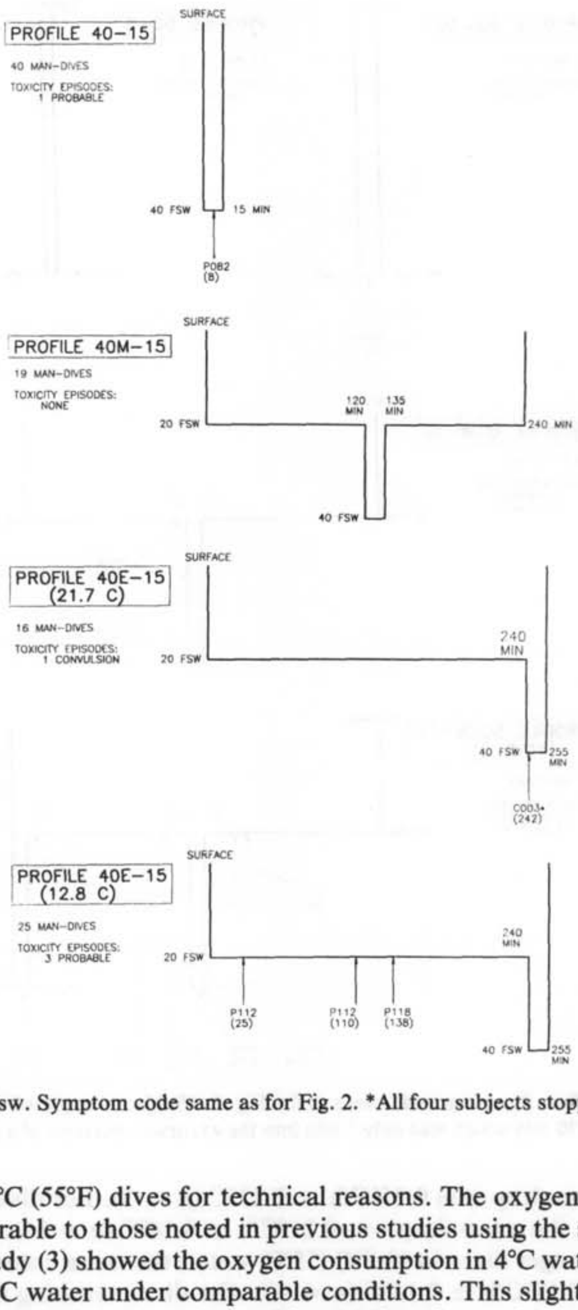

Fig. 4. Profile 40 fsw. Symptom code same as for Fig. 2. *All four subjects stopped.

sured on the 12.8°C (55°F) dives for technical reasons. The oxygen consumptions at 21.7°C are comparable to those noted in previous studies using the same protocol (3, 5). A previous study (3) showed the oxygen consumption in 4°C water was 0.09 l/min higher than in 21°C water under comparable conditions. This slight increase may be due not only to metabolic response to cold water but also to the increased hydrodynamic resistance of moving legs in a full wet suit as compared to bare legs.

Core temperature changes

For the 4-h or longer dives in 21.7°C (71°F) water, the mean core temperature drop for all dives was 0.23°C/h ± 0.16°C (n = 93). For dives resulting in oxygen toxicity

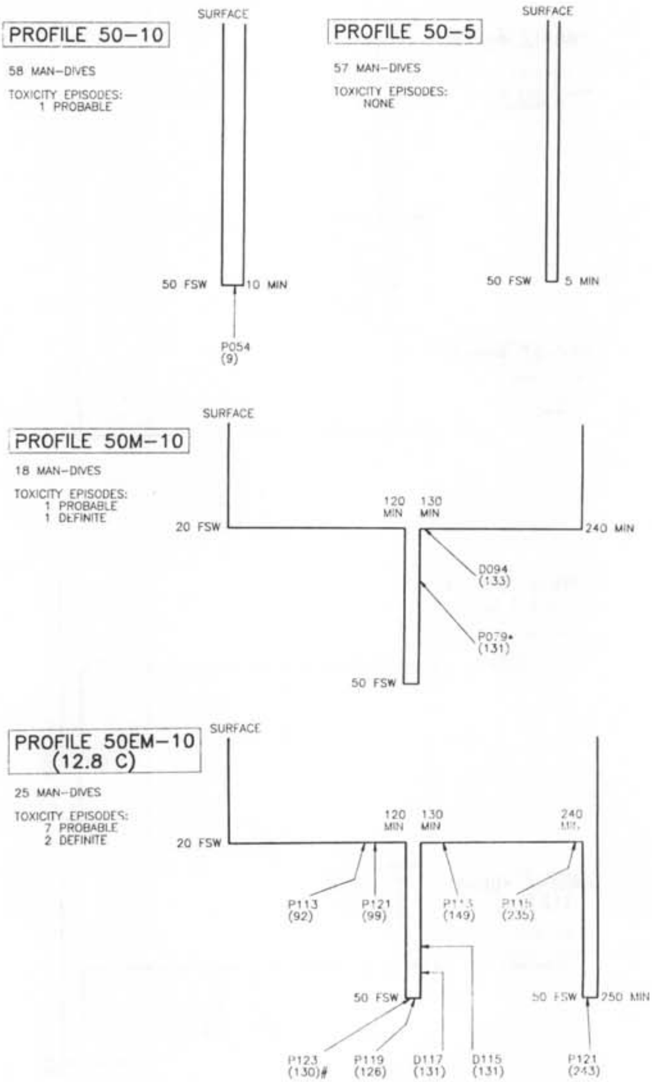

Fig. 5. Profile 50 fsw. Symptom code same as for Fig. 2. *Subject completed entire profile. **Onset of symptoms was at 130 min which was only 3 min into the excursion because of a delayed descent.

episodes, the mean drop was 0.35°C/h ± 0.13°C (n = 9). For dives not resulting in toxicity episodes, the mean drop was 0.21°C/h ± 0.16°C (n = 84).

For the 4-h or longer dives in 12.8°C (55°F) water, the mean core temperature drop for all dives was 0.19°C/h ± 0.14°C (n = 46). For dives resulting in oxygen toxicity episodes, the mean drop was 0.30°C/h ± 0.14°C (n = 10), while the mean drop for dives not resulting in toxicity episodes was 0.16°C/h ± 0.12°C (n = 36).

The rate of core temperature drop in 12.8°C (55°F) water was not as great as in 21.7°C (71°F) water, indicating that the full wet suit at the lower temperature provided more thermal protection than a wet suit top or shorty wet suit in 21.7°C (71°F) water. The core temperature drop rate was greater in dives resulting in oxygen toxicity compared to those not resulting in symptoms. For the 21.7°C (71°F) water dives, this

TABLE 4
OXYGEN TOXICITY EPISODES BY DIVE PROFILE

Profile*	Dive, No.	Subject, No.	Class of Toxicity	Signs and Symptoms (In order of occurrence)	Time** Reported, min	Comments†, ‡, §
25–240			None			
30–90	109	16	Convulsion	Nausea Convulsion	82	Noted onset of nausea approximately 6 min before convulsion. Convulsion occurred about 15 s after discontinuing oxygen breathing.
35–30	006	25	Probable	Decreased auditory acuity Generalized tingling	12	Decreased auditory acuity was present for 2 min before onset of tingling.
35–30	012	25	Definite	Muscle twitching	25	Diffuse twitching of right leg muscles, lasted about 10 s.
35–30	017	38	Definite	Muscle twitching Aphasia	29	Began in right calf, spread to include both arms and legs, lasted 15 s.
35–30	017	40	Definite	Tinnitus Confusion Muscle twitching	29½	Had tinnitus briefly at onset. Left leg twitching, lasted 2 min.
35–30	002	46	Definite	Decreased auditory acuity Muscle twitching	29½	Thigh, calf, and foot twitching. Above symptom preceded by 2 min of decreased auditory acuity.
35–25			None			

TABLE 4 (continued)

Profile*	Dive, No.	Subject, No.	Class of Toxicity	Signs and Symptoms (In order of occurrence)	Time** Reported, min	Comments[†, ‡, §]
35 M–25	034	18	Probable	Generalized numbness Generalized tingling Poor concentration Dizziness	5	Occurred after only 5 min at 20 fsw.
35 M–25	064	37	Definite	Muscular twitching Muscular rigidity Amnesia Confusion Aphasia	137	Bilateral leg twitching. Hands had to be pried from ergometer. Amnesiac for short period during the toxicity episode. Confused and aphasic for 2 min after twitching stopped.
35 E–25	070	19	Probable	Nausea Tinnitus	20	Tinnitus, 20 min into dive-constant. Nausea, 45 min into dive, intermittent throughout. *See* comments for below dive (same diver). Dive completed, symptoms reported postdive.
35 E–25	066	19	Probable	Nausea Tinnitus	30	Tinnitus persisted steadily throughout rest of dive, subject stated that this symptom is usually present on his O_2 dive. Nausea (also at 30 min) lasted 15

						min, recurred at 2-h. Subject stated he often has nausea on O_2 dives. Dive completed, symptom reported postdive.
35 E–25	097	3	Probable	Nausea Generalized tingling	147	Present 2 min before reporting.
35 E–25	066	16	Probable	Nausea	235	Occurred in trunk when changing bottle.
35 E–25	072	3	Definite	Nausea Muscle twitching	260	Nausea occurred briefly earlier in dive (110 and 210 min). Twitching of left thumb at 260 min, lasted 1 min. Twitching left eye at 264 min, persisted final 1 min, stopped after 30 s of gas. Dive completed, symptoms reported postdive.
35 EM–25	107	19	Probable	Tinnitus Nausea	142	*See* comments for dives 066 and 077 profile 35 E–2. Tinnitus began 5 min into dive. Nausea began 5 min into dive, intermittent, became more severe at 120 min during descent for excursion.
35 EM–25	110	8	Probable	Nausea	150	Noted queasy feeling for entire first part of dive. Had nausea for 25 min when reported, mild in intensity.

TABLE 4 (continued)

Profile*	Dive, No.	Subject, No.	Class of Toxicity	Signs and Symptoms (In order of occurrence)	Time** Reported, min	Comments[†, ‡, §]
						Nausea lasted 5 min after being reported. Dive completed.
35 EM–25	102	16	Probable	Dysphoria	246	Diver reported that he "just didn't feel right" and felt "ready to black out," 6 min into second excursion. This feeling present 1 min before being reported.
40–15	082	27	Probable	Nausea	8	Lasted 30 s. Dive completed, symptom reported postdive.
40 M–15			None			
40 E–15	003	16	Convulsion	Tinnitus Muscle twitching Convulsion	242	Had 1 min of tinnitus before getting off ergometer. Noted both hands shaking immediately before getting off ergometer. Convulsed 10 s after getting off ergometer.
40 E–15 (55° Water)	112	6	Probable	Dizziness Dysphoria Nausea	25	Dizziness and dysphoria (described as "just didn't feel right in my head") present about 30 s. Stopped dive as soon as nausea began.

40 E–15 (55° Water)	112	10	Probable	Nausea Dizziness	110	Nausea present 3 min. Stopped dive at onset of dizziness.
40 E–15 (55° Water)	118	12	Probable	Nausea	138	Nausea present for 3 min before dive stopped.
50–5			None			
50–10	054	16	Probable	Generalized tingling Dizziness	9	Lasted 2 min. Dive completed, symptom reported postdive.
50 M–10	079	16	Probable	Lightheadedness	131	Occurred during ascent from 50 fsw. Passed quickly. Dive completed.
50 M–10	094	4	Definite	Muscle twitching Dysphoria	133	Lip twitching and right leg twitching began during ascent from 50 fsw (131 min). Dysphoria described as "not thinking right."
50 EM–10 (55° Water)	113	4	Probable	Nausea	92	Present 30 min, moderate. Diver stated he often has nausea during operational O_2 swims.
50 EM–10 (55° Water)	121	4	Probable	Nausea Dizziness	99	Nausea present constantly since 30 min into dive. Dizzy 15 min before stopping dive.
50 EM–10 (55° Water)	119	15	Probable	Dizziness Choking sensation	126	Both symptoms occurred at the same time.
50 EM–10 (55° Water)	123	3	Probable	Dizziness Choking sensation Increased respiratory rate	130	Had problems with belching into mouthpiece and gas leaking from face mask during early part of dive.

TABLE 4 (continued)

Profile*	Dive, No.	Subject, No.	Class of Toxicity	Signs and Symptoms (In order of occurrence)	Time** Reported, min	Comments†, ‡, §
						Symptoms began at 130 min which was only 3 min into 50 fsw instead of at end because of delayed excursion (another diver had difficulty clearing). Choking sensation, lasted 10 min after discontinuation of O_2 breathing.
50 EM–10 (55° Water)	113	29	Probable	Nausea	149	Had nausea transiently beginning at 127 min and lasting about 3 min. Brief recurrence just before 149 min.
50 EM–10 (55° Water)	115	1	Probable	Decreased mental alertness Numbness Dizziness	235	Decreased mental alertness present for 4 min. Bilateral leg numbness and dizziness developed at 235 min.
50 EM–10 (55° Water)	121	20	Probable	Dysphoria	243	Diver had dysphoria 3 min into second excursion to 50 fsw, described as "a sudden rush all over my whole body."
50 EM–10 (55° Water)	115	18	Definite	Visual disturbances Nausea Confusion	131	During ascent from 50 fsw, noted that platform was appearing to move, both left and right as well as nearer and farther away.

						Nausea began about same time.
50 EM–10 (55° Water)	117	4	Definite	Dizziness Muscular twitching	131	During ascent from 50 fsw, noted 30 s of dizziness followed by twitching of right side of mouth.

*Profiles conducted in 71° F water unless otherwise noted. **Times recorded in this column represent time the diver stopped the work-rest cycle and reported that he felt he was experiencing a symptom compatible with oxygen toxicity. An exception to this general rule is made in the case of divers who reported symptoms but did not do so until the dive was completed. In these cases, the time recorded represents the estimated time of symptom onset as reported by the diver. †Most of the times recorded here were estimates by the divers obtained during a postdive interview and, as such, are regarded as approximate times. ‡All divers were recovered from the wet chamber at the time the symptom was reported unless otherwise noted. §All signs and symptoms noted resolved rapidly after cessation of oxygen breathing unless otherwise noted.

difference was significant at the 0.05 level using the two-tailed *t*-test for independent means. For the 12.8°C (55°F) water dives, the difference was significant at the 0.01 level.

Incidence of signs and symptoms of oxygen toxicity

Table 5 provides a description of the relative frequency of occurrence of the various signs and symptoms of oxygen toxicity. Nausea was the most frequently reported symptom, with 16 separate occurrences; muscle twitching and dizziness both were observed 9 times. Tinnitus was encountered on 5 occasions and dysphoria (used here to describe several different episodes in which the diver reported vague, generalized feelings of ill-being, such as "I just didn't feel right" or "I felt like I was going to black out," etc.) was reported 4 times. Confusion was reported 3 times and a variety of other signs and symptoms were observed once or twice. It should be noted that most of the divers encountered a transient unsteadiness when they first resumed a standing position in the wet chamber after a period of pedaling the bike, submerged

TABLE 5
SYMPTOMS OF O_2 TOXICITY AND THEIR FREQUENCY OF OCCURRENCE

Signs/Symptom	Toxicity Episodes in Which Symptoms Were Observed	Percent of Total Symptoms	Percent of Toxicity Episodes in Which Symptoms Were Observed
Nausea	16	24.6	48.5
Muscle Twitching	9	13.9	27.3
Dizziness	9	13.9	27.3
Tinnitus	5	7.7	15.2
Dysphoria	4	6.2	12.1
Confusion	3	4.6	9.1
Convulsion	2	3.1	6.1
Decreased Auditory Acuity	2	3.1	6.1
Aphasia	2	3.1	6.1
Tingling	2	3.1	6.1
Numbness	2	3.1	6.1
Choking Sensation	2	3.1	6.1
Amnesia	1	1.5	3.0
Muscular Rigidity	1	1.5	3.0
Lightheadedness	1	1.5	3.0
Poor Concentration	1	1.5	3.0
Visual Disturbances	1	1.5	3.0
Decreased Mental Alertness	1	1.5	3.0
Increased Respiratory Rate	1	1.5	3.0
Total Symptoms	65	100	
Total Toxicity Episodes	33		

in the horizontal position. Because of the preponderance of this symptom and the predictable nature of the time and duration of its occurrence, vestibular and/or orthostatic factors were felt to be a more likely etiology than oxygen toxicity. The last column in Table 5 shows the percent of total toxicity episodes that included that particular symptom. The frequencies differ from the percent of total symptoms because more than one symptom occurred during many of the toxicity episodes. Thus, while nausea accounted for about one quarter of all symptoms it was observed on almost half of all toxicity episodes.

DISCUSSION

Establishing limits

The purpose of this study was to establish depth-time oxygen exposure limits for open water operational dives. The results of this study are of scientific interest, but some of the decisions that had to be made regarding safe exposure limits were not necessarily made on purely scientific grounds.

One of the major difficulties in evaluating the safety of a proposed schedule for oxygen diving lies in determining the relative importance of various toxicity episodes. We have previously described our classification of episodes as convulsion, definite, or probable. In deciding whether or not a given exposure is safe for operational use, the occurrence of two grand mal seizures would certainly be of greater significance than the reporting of two "I'm not sure what it was, but I just didn't feel right" type toxicity episodes. Previous studies (5) have shown that even in an experimental environment in which such variables as inspired CO_2 and exercise rate can be closely controlled, an occasional convulsion may occur well within what other experimental work and long-time operational use have shown to be safe limits.

The decision-making process used in arriving at safe exposure limits is best explained by using specific examples as illustrations. On some profiles there was a grouping of unmistakable episodes of oxygen toxicity conveniently clustered near the end of the exposure. The profiles were accordingly adjusted and the shortened exposures were conducted without further incident. The 40-fsw square dive limit in the 1982 NEDU study was an example of this type of situation. The 20-min exposure resulted in 2 convulsions in only 17 dives, one at 19 min and the other at 20 min. Reduction of the exposure time to 15 min resulted in no definite episodes or convulsions in 24 exposures. Forty more man-dives in the current study were also free of definite episodes or convulsions. Another example is that of the 35-fsw square dive limit. Forty dives using a 30-min limit resulted in 4 definite toxicity episodes, all occurring at 25 min or later. No definite toxicity episodes or convulsions were noted on 47 subsequent 25-min exposures. Clear-cut groupings of toxicity episodes such as these require no agonizing, and establishing the safe exposure time limit is straightforward.

More difficult decisions must be made when faced with single toxicity episodes that occur in the latter part of an exposure which is otherwise free from serious toxicity episodes. As an example, 36 man-dives at 30 fsw for 90 min were accomplished without a single sign of oxygen toxicity; on the last dive, however, one diver had a convulsion at 82 min. It is acknowledged that simply reducing the allowed exposure time to less than that resulting in the single toxicity episode certainly does not eliminate the possibility of toxicity episodes occurring. One feels reluctant, however, to recommend an exposure time observed to cause convulsions when, by a relatively small reduction in exposure time, limits can be proposed that both allow a diver reasonable operating time at a given depth and yet have not been observed to result in any significant oxygen toxicity. Establishing an exposure limit of 80 min at 30 fsw accomplishes both of these objectives. Implicit in such decisions is the need to strike a workable balance between a single oxygen toxicity episode and operational safety.

A different situation exists when a single toxicity episode is noted that is completely anomalous when compared to the results of all the other exposures at that depth. The 1982 NEDU study saw one diver convulse after only 72 min on oxygen at 25 fsw. Twenty-five other exposures at 25 ft for 2 h were completely free of toxicity episodes. In addition, 22, 4-h exposures at 25 fsw in our current dive series were completely free of any signs or symptoms of oxygen toxicity. Another striking example in the current dive series is the occurrence of a convulsion during a 40-fsw excursion on Profile 40 E–15 after only 2 min at 40 fsw. This episode was inconsistent with our general experience with 40-fsw excursions. Fifty-six other 40-fsw, 15-min excursion exposures resulted in no definite toxicity episodes or convulsions. Shortening the exposure limits to accommodate these isolated and anomalous toxicity episodes would result in limits that are unreasonably restrictive in light of the total body of experimental data. Rather they attest to the unpredictable nature of CNS oxygen toxicity, which defies attempts to establish limits that can be guaranteed free of any toxicity episodes for all divers and mandates that closed-circuit oxygen swimmers be aware of this fact and be prepared to deal with symptoms should they occur. (It must also be noted that both of these anomalous toxicity episodes occurred in individuals who were reproducibly oxygen-sensitive, as discussed later.) Acknowledging the possibility of occasional episodes of oxygen toxicity even on seemingly innocuous oxygen dives, the U.S. Navy has made a safety line connecting the 2 divers in a swim pair mandatory for closed-circuit oxygen diving operations.

Less weight was placed on the occurrence of probable episodes. Nausea was by far the most commonly observed symptom seen in probable episodes; both Donald (4) and Yarborough et al. (8) described nausea as being present intermittently in some of their subjects and not being a good indicator of imminent severe symptoms. Most of the probable episodes were very mild and the divers often stated that they could have finished the dive; several dives were in fact completed despite mild, transient symptoms early in the dive and were not reported until postdive. One diver, as will be discussed later, had constant tinnitus and intermittent nausea throughout several of his dives. It should also be noted that the probable episodes tended to occur in a random distribution throughout the dive (Figs. 2–5) rather than being grouped near the end of an exposure to suggest a logical end point. Lastly, all divers who experienced toxicity episodes labeled as probable would have been able to surface and begin breathing air; no symptoms that incapacitated a diver or caused him to have an obvious decrement in his motor or cognitive abilities were placed in the probable category. For these reasons, exposures on which only probable symptoms occurred are generally considered to be acceptable.

Single depth oxygen exposures

The 4-h exposure at 20 fsw was by far the most numerous of our experimental exposures. All 4-h profiles where there was no toxicity during the downward excursion at 2 h were included in establishing the 20-fsw exposure time limit. Of the 161 exposures done, 153 dives met this criteria (allowable exposures). A total of 12 toxicity episodes, all probable, occurred. (Note that any symptoms occurring within 5 min after an excursion were considered to have been caused by the excursion.) Figure 6 shows that these toxicity episodes were scattered randomly throughout the dive and were not grouped around a particular point in time that would represent a logical end point. This 4-h exposure at 20 fsw, therefore, is considered safe. It should be noted that the 4-h figure represents only the upper limit of the exposure times tested in this series. A longer exposure limit at 20 fsw may be possible, but was not tested.

Twenty-two man-dives were accomplished at 25 fsw for 4 h with no symptoms of oxygen toxicity noted. These data indicate that 25 fsw for 4 h is an acceptable exposure time limit, despite the single convulsion at 25 fsw occurring during a previous study (5), as discussed above.

Figure 2 shows that 37 man-dives were conducted on Profile 30–90 with 1 convulsion occurring at 82 min. Three additional dives were completed to 82 min but stopped

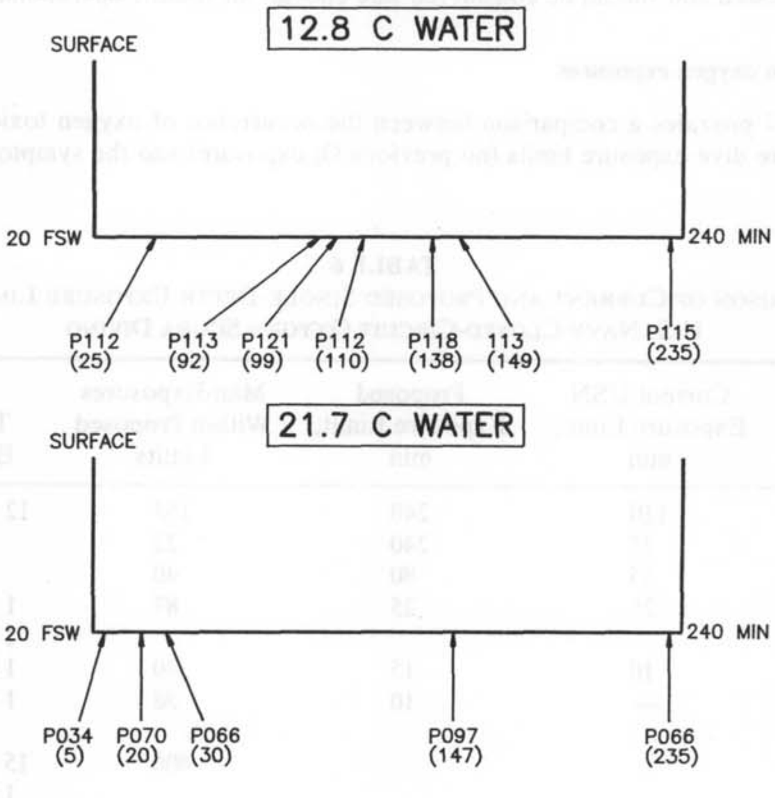

Fig. 6. Toxicity episodes at 20 fsw.

at that time because of the convulsion. The single convulsion resulted in the safe exposure time limit being reduced to 80 min, for the reasons discussed earlier. Since the single toxicity episode occurred after the 80-min proposed limit, a total of 40 man-exposures were accomplished within this limit without any evidence of oxygen toxicity.

On the 35-fsw single depth profile, all but one oxygen toxicity episode occurred after 25 min (Fig. 3). The single episode occurring at 12 min was a probable symptom and was not considered in establishing a safe exposure time limit. The tight grouping of the 4 definite episodes led to 25 min being recommended as the maximum exposure time at 35 fsw.

Forty exposures at 40 fsw for 15 min with only 1 probable symptom confirmed the previous NEDU findings (5) that 15 min was the safe exposure limit at 40 fsw. The previous NEDU study demonstrated clearly that 20 min at 40 fsw was unsafe.

A 10-min exposure to 50 fsw was found to be safe in 58 square dives. A 15-min exposure at 50 fsw was not tested, nor were any exposures deeper than 50 fsw.

Table 6 shows the current U.S. Navy oxygen exposure limits, the proposed limits from this study, the number of man-exposures done within the proposed limits, and the number of oxygen toxicity episodes that occurred within the proposed limit.

All exposures using pure oxygen below 25 fsw are currently considered "exceptional exposure" by the U.S. Navy and require specific justification for use. With the additional data that this study provides, exposure limits below 25 fsw are felt to be well tested and should be considered safe enough for routine operational use.

Excursion oxygen exposures

Table 7 provides a comparison between the occurrence of oxygen toxicity from the square dive exposure limits (no previous O_2 exposure) and the symptom occur-

TABLE 6

COMPARISON OF CURRENT AND PROPOSED SINGLE-DEPTH EXPOSURE LIMITS FOR U.S. NAVY CLOSED-CIRCUIT OXYGEN SCUBA DIVING

Depth, fsw	Current USN Exposure Limit, min	Proposed Exposure Limit, min	Man-Exposures Within Proposed Limits	Toxicity Episodes
20	110	240	153	12 Probable
25	75	240	22	0
30	45	80	40	0
35	25	25	87	1 Definite 1 Probable
40	10	15	40	1 Probable
50	—	10	58	1 Probable
Total			400	15 Probable 1 Definite

TABLE 7

OXYGEN TOXICITY OCCURRING DURING DOWNWARD EXCURSIONS

			Symptom Type* and Frequency			
			Total Man Exposures	C	D	P
35 fsw (Exposure times of 25 min)						
No previous O_2 exposure	35–25		47	0	0	0
	35–30		40	0	1	1
Total			87	0	1	1
2-h pre-exposure at 20 fsw	35 M–25		19	0	1	0
	35 EM–25		16	0	0	2
Total			35	0	1	2
4-h pre-exposure at 20 fsw	35 E–25		17	0	1	0
	35 EM–25		15	0	0	1
Total			32	0	1	1
40 fsw (Exposure times of 15 min)						
No previous O_2 exposure	40–15		40	0	0	1
2-h pre-exposure at 20 fsw	40 M–15		19	0	0	0
4-h pre-exposure at 20 fsw	40 E–15	71°F	16	1	0	0
		55°F	22	0	0	0
Total			38	1	0	0
50 fsw (Exposure times of 10 min)						
No previous O_2 exposures	50–10		58	0	0	1
2-h pre-exposure at 20 fsw	50 M–10		18	0	1	1
	50 EM–10	55°F	23	0	2	2
Total			41	0	3	3
4-h pre-exposures at 20 fsw	50 EM–10	55°F	17	0	0	1

*C = Convulsion D = Definite P = Probable. Exposures where oxygen toxicity symptoms at 20 fsw did not occur within 5 min of downward excursions are not counted in totals.

rence for the same exposure time when undertaken after a 2- or 4-h pre-exposure at 20 fsw.

In analyzing the effects of the 20 fsw pre-exposures on subsequent excursion times, only convulsions and definite symptoms were considered. Probable symptoms are included in Table 7 only for completeness. Also note in Table 7 that EM exposures are considered twice because they had excursions after both a 2- and 4-h pre-exposure. The difference in total man-exposures for EM profiles between the 2nd and 4th h entry reflects the number of oxygen toxicity episodes occurring between the 2- and 4-h excursion.

Table 7 shows that for a 35-fsw excursion during the long profiles the frequency of definite oxygen toxicity episodes after a 2-h pre-exposure to 100% oxygen at 20 fsw was approximately the same as after a 4-h pre-exposure. On the short square dives, one definite symptom occurred but almost twice as many man-exposures were done. The definite episodes during the long dive excursions tended to occur earlier (17 min after a 2-h pre-exposure, 20 min after a 4-h pre-exposure) than the one during the square dive (25 min). Based on these small number of episodes all that one can say is that it appears that the probability of a definite toxicity episode after a 2-h pre-exposure will be slightly increased over that for a square dive but that the length of pre-exposure is unimportant.

The situation for the 40-fsw dives is much the same. One convulsion occurred after a 4-h pre-exposure and this was in the same diver who convulsed after 82 min at 30 fsw. It is difficult to make any definitive statements from this isolated episode.

At 50 fsw there was a pronounced increase in definite symptoms after a pre-exposure if the dives at 12.8 and 21.7°C are considered together. However, two of the three episodes occurred on the 12.8°C dives. One might postulate that the cold water exposure increased the likelihood of oxygen toxicity episodes, but the 17 dives free of definite symptoms after the 4-h pre-exposure do not confirm this. The data here are not sufficient to draw any hard conclusions because the divers who showed oxygen toxicity symptoms during the 2-h period preceding the first excursion did not complete the dive. Thus, the magnitude of the selective screening effect of the first 2-h pre-exposure and excursion is unknown and may account for the lack of definite symptoms after a 4-h pre-exposure.

The only generalization we can make from Table 7 is that while it appears that a 2-h pre-exposure may slightly increase the probability of a definite oxygen toxicity episode there is no consistent pattern of increased episodes to indicate that a 4-h pre-exposure is any worse than a 2-h pre-exposure.

Based on the results of the excursion exposures discussed above, the following operational limits are recommended: 15 min for excursions to 40 fsw and shallower; 5 min for excursions from 41 to 50 fsw. These excursion limits presume a pre-exposure of 240 min or less at a depth of 20 fsw or shallower. Only a single excursion has been recommended for the present which, although conservative, allows for operational simplicity until additional research is done and final guidelines established.

Pre-exposure depth

One definite conclusion which can be established from the excursion profiles done here is that a pre-exposure depth of 20 fsw has much less effect on a subsequent excursion than 25 fsw. The previous NEDU study (5) showed 2 definite symptoms out of 13 man-exposures during a 15-min excursion to 40 fsw after only a 2-h pre-exposure to 100% oxygen at 25 fsw. By contrast, in this study there were no symptoms in 19 exposures following a 2-h pre-exposure at 20 fsw and only 1 in 38 exposures following a 4-h pre-exposure at 20 fsw.

Double excursion profiles

The interval at 20 fsw between the excursions (which ranged from 95–110 min) on the double excursion profiles appeared to provide nearly complete recovery from any presumed latent toxicity incurred as a result of the first excursion. On Profile 35 EM–25, 16 first excursion exposures resulted in 2 Probable toxicity episodes, whereas 15 second excursion exposures resulted in only 1 Probable toxicity episode. On Profile 50 EM–10, 23 first excursion exposures resulted in 2 Probable and 2 Definite toxicity episodes, while 18 second excursion exposures resulted in only 1 Probable toxicity episode.

It is possible that the first excursion on these profiles may have served as a de facto screening test, thus preventing relatively sensitive individuals from continuing on to the second excursion. This caveat makes it difficult to claim that the second excursion was actually less stressful than the first as would seem the case at first glance, but there is certainly no evidence to support any claim that the second excursion resulted in more toxicity than the first. This fact has significant operational implications in that it might allow a diver to make additional excursions on a mission provided he had returned to the transit depth of 20 fsw or shallower for a specified period of time before the next excursion. The periods at 20 fsw used in this study (95–110 min) appear to provide adequate time for the dissipation of any accumulated toxic effects. The minimum time at 20 fsw necessary to provide adequate recovery time is unknown and should be the subject of further investigation.

Symptoms of oxygen toxicity

Examination of the symptoms of oxygen toxicity observed during this study (Tables 4 and 5) provides an interesting contrast to those reported in the 1982 NEDU study (5). The most common symptoms in that series were lightheadedness, dysphoria, and apprehension. Nausea was not reported a single time; in fact, rather surprisingly so in that it was very common in other studies (4, 8). This study saw nausea reported more frequently than any other symptom, accounting for 24.6% of the total symptoms. Muscle twitching and dizziness were also very commonly seen.

One diver had a symptom pattern worthy of special note. Diver 19 made 3 experimental dives. He completed the first 2 long profiles despite the early appearance of a constant tinnitus and intermittent nausea (Table 4) and did not report these symptoms until postdive. On the 3rd long dive (Profile 35 EM–25), he again had tinnitus and nausea from early on, but stopped the dive after 22 min of the first 35 fsw excursion because the nausea became more severe. This individual remarked that he experienced these symptoms to a greater or lesser degree every time he made an oxygen swim but had never had any more serious problems ensue. In this individual, at least, tinnitus and nausea are obviously not reliable indicators of an imminent severe episode of CNS oxygen toxicity.

Individual sensitivity

Donald (4) described the marked individual variation in oxygen tolerance between individuals. Because of this ''inter-individual'' variation, all U.S. Navy diving candidates must pass an Oxygen Tolerance Test (OTT) before beginning diver training. This test consists of breathing pure oxygen at a partial pressure of 2.8 ATA for 30 min at rest in a dry chamber. This test is designed to identify oxygen-sensitive individuals and prevent them from being exposed to hyperoxic conditions under more hazardous operational diving conditions.

This study and the 1982 NEDU study (5), however, have provided 3 examples of individuals who displayed a marked susceptibility to CNS oxygen toxicity based on a high frequency of symptom occurrence in their experimental dives (Table 8) despite having previously passed an oxygen tolerance test. Two of the divers were enlisted Navy oxygen divers; the third was a Navy Diving Medical Officer with previous oxygen diving experience. Diver 16 in the 1982 NEDU study (5) was the individual who experienced the convulsion after 72 min at 25 fsw, an exposure which had never resulted in convulsive symptoms in previous experimental oxygen dive series; Diver 16 in the 1983 NEDU study experienced a convulsion on Profile 40 E–15 after only 2 min at 40 fsw. This diver accounted for 6 of the 33 toxicity episodes (18%) noted during this dive series although he made only 2% of the dives.

Donald (4) also described day-to-day variation in oxygen tolerance in the same individual (intra-individual variation). Because of this observation, multiple oxygen tolerance tests (no more than one per day) were administered to these 3 divers to see if additional tests would provoke any evidence of oxygen toxicity. Table 8 also lists the number of oxygen tolerance tests passed by these individuals (the figures shown reflect their initial test plus additional tests done after the divers were identified as being sensitive). The relative insensitivity of the Navy oxygen tolerance test is shown by the failure of these repeated tests to produce any symptoms of CNS oxygen toxicity in these individuals who had been shown to be relatively susceptible. This observation and its implication for the U.S. Navy screening test for oxygen intolerance are discussed more fully in a separate paper (14).

TABLE 8

OXYGEN SENSITIVE DIVERS

Diver No.	Age, yr	Height, cm	Weight, kg	Toxicity Episodes	Number of Dives	Oxygen Tolerance Tests
16 (1982)	33	193	84.1	2 Convulsions	3	10
1 (1982)	35	180	86.4	1 Convulsion 1 Definite	4	5
16* (1983)	27	193	81.8	2 Convulsions 4 Probable	11	2

*This diver is not the same individual shown above; the diver numbers are the same but the second diver was in the 1983 dive series.

Temperature effects

The correlation of core temperature change rate with the occurrence of oxygen toxicity indicates that divers who suffered episodes of oxygen toxicity had a more rapid rate of core temperature drop than those divers who did not encounter episodes of oxygen toxicity.

The following observations provide additional information regarding the thermal stress evoked by this dive series. In the 21.7°C (71°F) water, only shorty wet suits or wet suit tops were worn. On the 4-h profiles, most divers complained of the cold and were at least somewhat uncomfortable. Many divers were observed to be shivering continuously during the latter part of the dive. Attempts by the divers to wear additional protective rubber products had to be periodically repelled. Of the 130 long profiles accomplished in 21.7°C (71°F) water, 1 diver was taken out of the water for an excessive core temperature drop and 3 divers stopped the dive on their own initiative because they felt they were too cold to continue. Of the 50 profiles accomplished in 12.8°C (55°F) water, only 1 dive was stopped because of the cold. When the 18 divers who participated in the 12.8°C (55°F) profiles were polled as to whether or not they were colder, about the same, or warmer than in the 21.7°C (71°F) water, the results were as follows: Colder – 3; Same – 5; Warmer – 10.

The literature provides several interesting descriptions of the interaction between cold stress and CNS oxygen toxicity. Poikilotherms have been reported to be relatively resistant to the toxic effects of hyperbaric oxygen; this protection was lost, however, when the animals were warmed (15). Grossman and Penrod (16) reported increased survival under hyperoxic conditions when rats were profoundly hypothermic, but a decrease in survival associated with an increase in oxygen consumption resulted when a milder degree of hypothermia was induced. Donald (4) found that both cold stress and heat stress resulted in decreased oxygen tolerance. No correlation was noted between the magnitude of core temperature drop and oxygen toxicity episodes in the 1982 NEDU study (5). In this study, however, where the *rate* of cooling rather than the magnitude of the core temperature drop is examined, a statistically significant difference is noted between those divers who suffered oxygen toxicity episodes and those who did not. Whether this increase in susceptibility is due to the increased cooling rate itself or to secondary effects of the cooling (increased shivering or exercise rate with a resultant rise in oxygen consumption) cannot be answered from our data. The increased susceptibility to oxygen toxicity induced by exercise has been well documented (4, 8, 17). The increased oxygen consumption brought about by shivering may duplicate the effect of exercise during a hyperoxic exposure. Anyone who has experienced the dubious pleasure of continuing a dive after the onset of shivering and cold-related discomfort can also easily postulate another possible connection between hypothermia and oxygen toxicity. A cold, miserable diver may be quick to attribute any minor symptom noted to oxygen toxicity and thereby terminate his dive.

SUMMARY

1. Symptom classification is a useful tool in evaluating symptoms of oxygen toxicity; exposure limits should generally be adjusted only as a result of definite symptoms or convulsions.

2. The following single-depth dive oxygen exposure limits are proposed:

20 fsw (6.1 msw) —240 min
25 fsw (7.6 msw) —240 min
30 fsw (9.1 msw) — 80 min
35 fsw (10.7 msw)— 25 min
40 fsw (12.2 msw)— 15 min
50 fsw (15.2 msw)— 10 min

3. A pre-exposure depth of 20 fsw has a lesser effect of increasing the probability of oxygen symptoms on subsequent downward excursions than 25 fsw.

4. Twenty fsw pre-exposures for 2 and 4 h seem to slightly increase the probability of an oxygen toxicity episode on subsequent excursions but there is no consistent difference between the effects of these two pre-exposure lengths.

5. A return to 20 fsw for periods of 95–110 min provided an adequate recovery period from an earlier excursion and enabled a second excursion to be taken without additional hazard.

6. Nausea was the most commonly noted symptom of oxygen toxicity, followed by muscle twitching and dizziness.

7. Dives on which oxygen toxicity episodes were noted had a more rapid rate of core temperature cooling than dives without toxicity episodes.

8. Three divers who had passed the U.S. Navy Oxygen Tolerance Test were observed to be reproducibly more susceptible to oxygen toxicity than the other experimental divers.

The authors express their appreciation to: Mrs. Carol Zingsheim who processed this manuscript; Mrs. Lillian Owens who helped to locate many of the references; HM2 Regina Coerver who assisted with the figures; LCDR Mike Curley, MSC, USN, who provided assistance in the statistical treatment of the data; and especially to the U.S. Navy officers and men who voluntarily placed themselves at hazard to accomplish this study.

The opinions or assertions contained in this article are the private views of the authors and are not to be construed as reflecting the view of the Department of the Navy or the Department of Defense.—*Manuscript received for publication March 1985; revision received October 1985.*

Butler FK Jr, Thalmann ED. Toxicité à l'oxygène du système nerveux central chez les plongeurs avec l'appareil en circuit fermé scuba II. Undersea Biomed Res 1986; 13(2):193–223.—La toxicité à l'oxygène du système nerveux central est présentement le facteur limitatif dans les opérations de nage/plongée sous-marines avec un équipement à l'oxygène en circuit fermé. Une série de plongées fut effectuée à l'Unité de plongée expérimentale de la Marine (NEDU) à Panama City, FL, afin de déterminer si ces limites peuvent être allongées avec confiance et aussi pour évaluer la possibilité d'entreprendre des excursions à des profondeurs accrues après un séjour préalable à une profondeur moindre pour diverses durées de temps. Un total de 465 hommeplongées fut effectué avec 14 profiles expérimentaux différents. En tout, 33 incidents de toxicité à l'oxygène furent observés, y compris 2 convulsions. Les symptômes furent classifiés comme probable, définitif, ou convulsion. Les résultats furent les suivants: (a) la classification des symptômes est un moyen utile pour l'évaluation des signes de toxicité à l'oxygène; les limites d'expositions sans danger devraient généralement être ajustées à la suite de symptômes "définitifs" ou de convulsions; (b) les limites suivantes pour la plongée à profondeur unique sont proposées:

20 fsw (6.2 msw)—240 min
25 fsw (7.2 msw)—240 min
30 fsw (9.1 msw)— 80 min
35 fsw (10.7 msw)— 25 min
40 fsw (12.2 msw)— 15 min
50 fsw (15.2 msw)— 10 min

(c) une exposition préalable jusqu'à 4 h à 20 fsw occasionne seulement une legère augmentation dans la probabilité d'apparition d'un symptôme de toxicité à l'oxygène durant des excursions subséquentes vers le bas; (d) une profondeur d'exposition préalable à 25 fsw aura des effets plus néfastes sur les excursions subséquentes que cellle de 20 fsw; (e) le retour à 20 fsw pour des périodes de 95 à 110 min semble fournir une période suffisante de recouvrement après une excursion et permet d'entreprende une deuxième excursion sans danger additionnel; (f) la nausée était le symptôme de toxicité à l'oxygène noté le plus fréquemment, suivit de contractions musculaires involuntaires et de l'étourdissement; (g) les plongées au cours desquelles des incidents de toxicité à l'oxygène furent observés avaient un taux plus rapide de refroidissement de la température centrale que les plongées sans incident de toxicité; (h) plusieurs plongeurs qui avaient réussi le test de tolérance à l'oxygène de la Marine américaine avec succès furent observés comme étant reproductiblement plus susceptibles à la toxicité à l'oxygène que les autres plongeurs expérimentaux.

toxicité à l'oxygène — exercice
test de tolérance à l'oxygène — hypothermie
convulsion à l'oxygène — ABU en circuit fermé
limites de l'exposition à l'oxygène

REFERENCES

1. US Navy Diving Manual. NAVSEA 0994-LP-001-9020 (Revision 1) July 1981.
2. Lanphier EH, Dwyer JV. Diving with self-contained underwater operating apparatus. Navy Experimental Diving Unit (NEDU) Rep 11-54, April 1954.
3. Piantadosi C, Clinton RL, Thalmann ED. Prolonged oxygen exposures in immersed exercising divers at 25 fsw. Navy Experimental Diving Unit (NEDU) Rep 4-80, March 1980.
4. Donald KW. Oxygen poisoning in man, I and II. Br Med J 1947; 1:667–672, 712–717.
5. Butler FK, Thalmann ED. Central nervous system oxygen toxicity in closed-circuit scuba divers. In: Bachrach AJ, Matzen MM, eds. Underwater physiology VIII. Proceedings of the eighth symposium on underwater physiology. Bethesda: Undersea Medical Society, 1984:15–30.
6. Middleton JR, Piantadosi CA. Evaluation of modified Draeger LAR V closed circuit oxygen rebreather. Navy Experimental Diving Unit (NEDU) Rep 5-79, August 1979.
7. Thalmann ED, Sponholtz DK, Lundgren CEG. Chamber-based system for physiological monitoring of submerged exercising subjects. Undersea Biomed Res 1978; 5:293–300.
8. Yarborough OD, Welham W, Brinton ES, Behnke AR. Symptoms of oxygen poisoning and limits of tolerance at rest and at work. Navy Experimental Diving Unit (NEDU) Rep 01-47, January 1947.
9. Butler FK, Thalmann ED. Purging procedures for the Draeger LAR V underwater breathing apparatus. Navy Experimental Diving Unit (NEDU) Rep 5-84, March 1984.
10. Lanphier EH. Oxygen consumption in underwater swimming. Navy Experimental Diving Unit (NEDU) Rep 15-53, September 1953.
11. Lambertsen CJ. Effects of hyperoxia on organs and their tissues. In: Lenfant C, ed. Lung biology in health and disease. Vol 8. Robin ED, ed. Extrapulmonary manifestations of respiratory disease. New York: Marcel Dekker, Inc., 1978:239–303.
12. Edmonds C, Lowry L, Pennefather J. Diving and subaquatic medicine. 2nd ed. Mosman, N.S.W. Australia: Diving Medical Centre, 1981:571 pp.
13. Clark JM. Oxygen toxicity. In: Bennett PB, Elliott DH, eds. The physiology and medicine of diving and compressed air work, 3rd ed. San Pedro, CA: Best Publishing Co., 1982:200–238.
14. Butler FK, Knafelc ME. Screening for oxygen tolerance in US Navy divers. Undersea Biomed Res 1986; 13: 91–110.
15. Faulkner JM, Binger CA. Oxygen poisoning in cold blooded animals. J Exp Med 1927; 45: 865–871.
16. Grossman MS, Penrod KE. Relationship of hypothermia to high oxygen poisoning. Am J Physiol 1949; 156:177–181.
17. Layter R, White WA. Oxygen poisoning in man, effect of exercise on time of onset of symptoms. Naval Medical Research Institute Research Project X-436, 1946.